Title: Pan-tropical climate interactions

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One sentence summary: A complete understanding of how the tropics affect global climate requires a unified perspective of inter-basin interactions.

Abstract: The El Niño-Southern Oscillation (ENSO), which originates in the Pacific, is the strongest and most well-known mode of tropical climate variability. Its reach is global and it can force climate variations of the tropical Atlantic and Indian Oceans by perturbing the global atmospheric circulation. Less appreciated is how the tropical Atlantic and Indian Oceans affect the Pacific. Especially noteworthy is the multi-decadal Atlantic warming that began in the late 1990s, as recent research suggests that it has influenced Indo-Pacific climate, the character of the ENSO cycle, and the hiatus in global surface warming. Discovery of these pan-tropical interactions provides a pathway forward for improving predictions of climate variability in the current climate, and for refining projections of future climate under different anthropogenic forcing scenarios.

Main text: Tropical ocean-atmosphere interactions significantly affect the global climate system with socio-economic impacts that are felt worldwide. The El Niño-Southern Oscillation (ENSO) (see **Box 1** for key concepts) in the Pacific is the most prominent and consequential climate variation on the planet, but there are other patterns of climate variability in the tropical Indian and Atlantic Oceans that also have societal impacts. How these various patterns of climate variability interact with one another is an ongoing matter of debate. In particular, the prevailing view for many years was that variability in the Pacific had major impacts on the other two tropical ocean basins, which in turn had only limited influence on the evolution of climate variability in the Pacific. Multiple lines of new evidence now suggest that this view is incomplete and inaccurate.

Discovery of the Indian Ocean Dipole (IOD) *(1, 2)*, for example, highlighted a climate scale fluctuation in the Indian Ocean that arises through ocean-atmosphere interactions somewhat similar to those that generate Pacific ENSO events. The consensus view originally was that ENSO was largely responsible for energizing the IOD through changes in the Walker circulation, but we now realize that year-to-year variations in Indian Ocean sea surface temperature (SST), related to the IOD and particularly the Indian Ocean Basin (IOB) mode, can significantly feed back onto the evolution of ENSO *(3, 4)*. Similarly, in the past decade, we have come to appreciate how important it is to understand the great diversity in amplitude, spatial pattern, and duration of individual

ENSO events because of how sensitive ENSO climate impacts are to the details of SST structure and evolution *(5, 6)*. We have also begun to recognize that the dynamics that govern this diversity involve two-way interactions between the Atlantic and Pacific Oceans *(7-10)*. In addition, the hiatus in global surface warming during the late 1990s was associated with an unprecedented intensification of the Pacific trade wind system and cooling of the tropical eastern Pacific *(11, 12)*. Although some studies highlight the role of Pacific only ocean-atmosphere feedbacks in forcing the intensified trade winds *(13, 14),* and there is the possibility that changes in external forcing (e.g., aerosols) might have contributed to this intensification (15), other studies suggest that a complete explanation may need to invoke forcing from decadal warming trends over the tropical Atlantic *(16, 17)* and Indian Oceans *(17, 18)* since the late 1990s.

The idea of pan-tropical interactions is not new *(19)* and such interactions should be expected because the three tropical basins are connected via the atmospheric circulation. Recent evidence suggests that these interactions are vigorous, and that the three tropical oceans are more tightly connected than previously thought *(16, 17).* There is emerging evidence, for example, that in the post-2000 period, the Atlantic Ocean exerted considerable influence on the Pacific and Indian Oceans *(7, 8, 10, 16, 17)*, impacting variability on interannual to decadal timescales. Specifically, this Atlantic influence contributed to decadal changes in ENSO properties and to the hiatus in surface global warming. However, fully-coupled climate models do not generate the observed warming hiatus and the associated changes in tropical variability, in part due to severe systematic biases in the Atlantic *(20-22)*.

Interactions with higher latitudes can also influence the character of seasonal to decadal timescale variability in the tropics and there is extensive literature on this topic *(23, 24)*. Our purpose here though is to review recent advances in our understanding of the dynamics of pan-tropical interactions, including their decadal fluctuations, implications for seasonal and multi-year predictions, and future climate projections. We show that the linkages between the Indian, Pacific, and Atlantic Oceans can be exploited for improved seasonal to decadal climate predictions. To fully realize the potential for improved prediction, climate model systematic errors, especially in the tropical Atlantic, must be significantly reduced. Reducing these errors would also greatly increase our confidence in model projections of future climate in the tropics.

Indo-Pacific interactions

The Pacific Ocean and the Indian Ocean are connected through the atmosphere, via the Walker circulation *(19)* (**Fig. 1A**), and through the ocean via the passages of the Indonesian Archipelago *(25)*. ENSO-induced changes in the Walker circulation often lead to an SST dipole pattern called the IOD *(1, 2)*, followed by a basin-scale warming *(26)* named the IOB mode *(27)*. This canonical evolution contributed to the perception that the Indian Ocean is slave to the Pacific, but new research revealed a more dynamic Indian Ocean and its active role in shaping Pacific climate.

Along with reduced summer monsoon rainfall over the Indian subcontinent *(28)* a developing El Niño can trigger a positive IOD by inducing easterlies over the equatorial Indian Ocean in boreal summer *(29)* (**Fig. 1B**), but the IOD can occur independently of *(30),* and impact on *(4),* ENSO. An IOD event usually develops in boreal summer, peaks in fall, and decays rapidly in the beginning of winter. A positive Bjerknes feedback (**Box 1**) fosters the IOD development *(1, 2)*. At its positive phase, cold anomalies in the eastern Indian Ocean and warm anomalies in the western Indian Ocean drive equatorial easterly wind anomalies in the central Indian Ocean that enhance the anomalous temperature difference in a positive feedback (**Fig. 1C**), that can occur without ENSO. Because the IOD is accompanied by a zonal dipole in atmospheric convection (**Fig. 1C**), its net effect on the Western Pacific winds, and consequently on ENSO, is uncertain *(31)*. However, strong positive IODs may induce anomalous westerly winds in the western Pacific, contributing to El Niño development *(31, 32)* (**Fig. 1D**). Thus although the observed statistical ENSO-IOD relationship appears consistent with the IOD being a response to ENSO *(33)*, the IOD is in part independent of ENSO and has the potential to increase ENSO prediction lead times *(3, 4)*.

The IOB, which is the dominant mode of interannual Indian Ocean SST variability, and stronger in variance than the IOD, commences its development in boreal winter. An IOB warming is largely driven by reduced surface evaporation and increased downward shortwave radiation in response to El Niño remote forcing *(26)*. It usually reaches its maximum amplitude in boreal spring *(26)*, about one season after the mature phase of ENSO (**Fig. 1E**). However, the IOB is not simply a passive response to ENSO either. ENSO excites the IOB like a battery charging a capacitor, but the IOB can exert its climatic influence beyond the lifetime of an ENSO event like a discharging capacitor *(27, 34)*. In the southwest Indian Ocean where the thermocline is shallow *(35, 36)*, westward propagating downwelling Rossby waves in response to the weakened Walker circulation induce SST warming beginning in boreal fall *(35)*. This warming strengthens atmospheric convection and triggers an asymmetric wind anomaly pattern across the equatorial Indian Ocean in boreal spring *(36)* (**Fig. 1E**). The anomalous wind pattern contributes to a subsequent warming in the north Indian Ocean through summer, which is in turn strengthened by a positive feedback with the northwest Pacific anomalous anticyclone by radiating an atmospheric Kelvin wave *(34)* (**Fig. 1F**). This coupled inter-basin mode leads to a strengthened Asian summer monsoon in the post-El Niño summer *(28, 37)*.

In contrast to the reinforcing role of a positive IOD, an IOB warming, though forced by El Niño, hastens El Niño's demise. As an El Niño matures, IOB warming induces enhanced convection over the Indian Ocean which in turn enhances the northwest Pacific anomalous anticyclone and easterly anomalies over the equatorial western Pacific *(3)* (**Fig. 1, D and E**). The advent of easterly surface wind anomalies from boreal winter to the following summer expedites the El Niño demise *(3, 38)*. The IOB hence damps ENSO variability and contributes to its biennial timescale, as corroborated by climate model experiments where the Indian Ocean is decoupled from the Pacific *(39-42)*. Despite their contrasting roles, a long-lasting IOB warming after a strong positive IOD may lead to a fast phase transition of El Niño to La Niña *(43)*. This is because an abrupt wind change is fostered by the sequence of events that starts with a positive IOD contributing to an El Niño, which in turn drives a strong IOB warming that then enhances central Pacific cooling *(43, 44)*.

The relationship between variability of the two oceans is time-varying and asymmetric about their positive and negative phases. ENSO exhibits a variety of spatial SST patterns, which have different consequences on the Walker circulation response *(45)*. The frequent occurrence of central Pacific (CP) El Niño events in recent decades *(46)*, which tend to have smaller amplitudes than corresponding eastern Pacific (EP) El Niño events, might explain a recent weakening of the ENSO-IOD relationship *(45, 47)*. Because SST and atmospheric deep convection anomalies over the Indo-Pacific are larger during El Niño compared to La Niña, an IOB warming is more efficient at influencing west Pacific wind anomalies during El Niño than La Niña. As such, the IOB warming is more efficient in contributing to the demise of El Niño than an IOB cooling to the demise of La Niña *(38, 48)*. This asymmetric response contributes to ENSO duration asymmetry, with La Niña typically lasting longer than El Niño *(48)*.

Although changes in the atmospheric Walker circulation dominate ENSO interactions with both the IOB and the IOD, the oceanic pathway across the Indonesian Seas has a prominent role in Indo-Pacific exchanges. This flow, termed the Indonesian Throughflow, is a major component of the global ocean circulation and plays a key role in the transport of mass, heat, and salt from the Pacific to the Indian Ocean *(25)*. Decadal changes in the Throughflow affect the background thermal structure of the Indian Ocean, which can in turn modulate IOD characteristics *(49)*. During the recent hiatus in global surface warming, increased heat uptake in the Pacific was shown to be partly transported to the Indian Ocean via the Throughflow *(50)*. However, recent studies suggest that the dynamics of the hiatus per se may involve interactions between the Atlantic and Indo-Pacific *(12, 16, 17)*.

Atlantic and Indo-Pacific interactions

Modeling and observational evidence suggests that two-way interactions between the tropical Atlantic and Pacific operate on interannual timescales *(10, 51)*. Tropical Atlantic variability, in part forced by ENSO, feeds back onto ENSO. For example, decoupling the Atlantic Ocean in otherwise fully coupled models generally leads to a stronger ocean-atmosphere coupling strength in the equatorial Pacific, a shift to a lower ENSO frequency, and an increase in ENSO variance *(10, 19, 39, 41, 42, 52, 53)*.

El Niño-induced atmospheric heating forces the tropical Atlantic through two distinct pathways, one of which is tropical and the other of which is extratropical. The tropical pathway involves a weakening of the Walker circulation that in turn generates anomalous descending motion over the tropical Atlantic *(24, 52)*. The extratropical pathway involves excitation of the Pacific–North American (PNA) pattern with an anomalously low surface pressure center over the western subtropical Atlantic *(54)* (red circles, **Fig. 1D**). As a result, the north tropical Atlantic (NTA; 10°N-20°N) (northern black box, **Fig. 2A**) warms significantly, peaking in boreal spring 3-5 months after an El Niño matures in December *(55)* (**Fig. 1E**). This NTA warming arises from reduced surface latent heat flux due to a weakening of north-easterly trades, associated with a PNA low pressure anomaly to the north, an anomalous descent to the south, and a sustained wind-evaporative-SST (WES) effect *(26)* (**Box 1**; **Fig. 1D**). Models appear able to capture this Atlantic response *(56, 57)*, but there is uncertainty as to the relative role of the tropical and extratropical processes. This is because the weakened northeasterly trades can be caused by the anomalous Walker and local Hadley cells *(58)*, a Gill-type response to Amazonian heating *(59)* (**Box 1**), or a tropospheric temperature warming in response to El Niño *(24, 60)*.

In turn, NTA anomalous warming has been suggested to impact ENSO. An NTA warming in boreal spring excites an atmospheric Rossby wave that propagates westward, causing northeasterly wind anomalies over the subtropical north-eastern Pacific *(8)* (**Fig. 2A**). This can generate cold SST and low rainfall anomalies in subsequent seasons, inducing a low-level anticyclone further to the west (**Fig. 2B**). The associated easterly wind anomalies in the western equatorial Pacific might in turn initiate a La Niña (**Fig. 2C**). An atmospheric Kelvin wave response to the NTA warming can also induce easterly anomalies through the Indian Ocean *(61)* (**Fig. 2, A and B**). This NTA forcing tends to favor the CP type of ENSO *(8, 10)*, consistent with an extratropical Pacific forcing of CP ENSO events *(62)*.

Another center of inter-basin interactions is the equatorial Atlantic (southern black box, **Fig. 2B**), where the Atlantic Niño dominates *(63)*. ENSO's influence on the equatorial Atlantic is not robust however, with only a weak concurrent correlation between ENSO and the equatorial Atlantic SST *(55, 64)*. During El Niño, a weakening Walker circulation and the associated easterly wind anomalies along the equator in the Atlantic (**Fig. 1B**) tend to generate cold anomalies through the Bjerknes positive feedback *(65)*. However, this cooling may be offset by either tropospheric warming in response to El Niño *(66)* and/or by oceanic downwelling Kelvin waves induced by a meridional SST gradient due to warming in the NTA, propagating into the region *(67)*. These competing effects may contribute a weak influence of ENSO on equatorial Atlantic SST and to the concurrent weak relationship between ENSO in the Pacific and the equatorial Atlantic SST.

By contrast, influence of the equatorial Atlantic on ENSO is robust since the 1970s, as reflected in a statistically significant negative correlation when an equatorial Atlantic Niño/Niña leads a

Pacific La Niña/El Niño by two seasons *(64, 68-70)*. For example, an Atlantic Niño, which peaks in boreal summer, induces anomalous ascending motion over the Atlantic and anomalous subsidence over the central Pacific (**Fig. 2B**). The associated easterly wind anomalies over the central and western equatorial Pacific excite an oceanic upwelling Kelvin wave that triggers the Pacific Bjerknes feedback, conducive to development of a La Niña event six months later *(71)* (**Fig. 2C**).

The role of the tropical Atlantic on ENSO variability is corroborated by pacemaker climate model experiments. When observed historical SST is prescribed over the tropical Atlantic, models are able to reproduce the observed impact on ENSO (**Fig. 2, D to F**) *(69-71)*. Figure 2 is based on the ensemble average of a five-member ensemble pacemaker experiment over the period of 1980-2005, in which full coupling is permitted everywhere except in the tropical Atlantic (30°S-30°N), where SSTs are nudged to observations. This, along with other pacemaker experiments, shows that the tropical Atlantic contributes to approximately 25% of Indo-Pacific SST variance *(69-71)*. However, as ENSO's impact on Atlantic Niño is not as robust as on the NTA, the two-way interaction of the Pacific with the NTA is stronger than with the equatorial Atlantic. An El Niño event during boreal winter can induce NTA warming in the ensuing spring (**Fig. 1E**), in turn contributing to the transition to a La Niña (**Fig. 2, C and F**) *(10)*. This interaction constitutes a delayed negative feedback for ENSO, shortening ENSO periodicity *(42)* as the IOB does *(3, 38)*.

This two-way interaction between NTA variability and Pacific ENSO has been reported to have strengthened since the late 1990s, coincident with the Atlantic Multi-decadal Variability (AMV, see **Box 1**) switch to a positive phase and an increasing tendency for biennial CP ENSO events *(8, 10)*. The positive phase of the AMV provides a warmer background NTA SST, which favors deep convection and a strengthening of the NTA influence on the Pacific. Such a feedback appears to be less active during a negative AMV phase, when the impact of the equatorial Atlantic tends to be stronger *(72)* because of a southward shift of the Inter-Tropical Convergence Zone (ITCZ). This shift leads to a stronger and wider westward extension of equatorial Atlantic interannual variability, facilitating a strong influence on the central and eastern Pacific *(73, 74)*. In addition, winds associated with a negative AMV phase may cause the tropical Pacific mean thermocline to shoal, increasing the mean stratification to favor enhanced ENSO variability *(75)*.

The impact of the tropical Atlantic extends to the Indian Ocean and the Western Pacific, affecting monsoons over these regions. An Atlantic Niño forces a Gill-type quadrupole response with a low-level anticyclone located over India and the western North Pacific suppressing the monsoon circulation *(76, 77)*. The competing impacts of the Atlantic and ENSO on the monsoons may explain the post-mid 1970s collapse of the ENSO-Indian monsoon relationship, in which a drier than normal monsoon typically precedes an El Niño peak *(76, 77)*. An alternative hypothesis is that observed decadal changes in the ENSO-Indian monsoon relationship are explained by the noise in the system *(78)*.

Rise of the tropical Atlantic influence

As discussed in Sections 2 and 3, ENSO characteristics can be significantly influenced by SST anomalies in the Indian and Atlantic Oceans. In this section, we describe similar inter-basin interactions that operate on decadal timescales, highlighting how interaction between the Atlantic and Indian Oceans with the Pacific Ocean changed in the 1990s. The Atlantic-Pacific connection now appears as the most prominent inter-basin interaction.

The IPO phase transition that occurred in the late 1990s has led to an unprecedented acceleration of the Walker circulation and contributed to the recent hiatus in global mean surface temperature *(11, 16, 17, 79)*, but what caused the IPO itself to change phase is not clear. The associated change in wind stress curl increases ocean heat uptake *(12, 80, 81)* and the strengthened Walker circulation intensifies the ITF, distributing the heat through the upper eastern Indian Ocean and the Indonesian Seas *(25, 80)*. Evidence suggests that the dynamics of these Pacific changes are not entirely internal to the Pacific, and forcing from the Indian and Atlantic Oceans needs to be considered *(12, 16, 82)*.

On decadal and multi-decadal timescales, the Indian Ocean also influences the Pacific through the tropical atmospheric bridge *(3, 38)*. Surface warming in the Indian Ocean, relative to the Pacific basin, leads to overlying deep convection and associated Walker circulation changes across the Indo-Pacific region that increase the surface easterlies in the western and central Pacific *(18)* (**Fig. 3A**). Because the temperature threshold for deep convection increases with the mean tropical temperature *(83)*, the relative warming can be represented by a tropical Indian-minus-Pacific trans-basin SST gradient to remove the mean tropical warming (blue curve, **Fig. 3C**). The trans-basin gradient displays a good relationship with the Pacific winds (black curve, **Fig. 3C**), which eventually drives a La Niña-like state through the Pacific Bjerknes feedback. But this relationship has weakened in recent decades *(82, 84)*, as indicated by reduced coherence between trends of Indian-minus-Pacific inter-basin SST gradients and equatorial central Pacific zonal wind stress (blue and black curves, **Fig. 3C**), but whether stochastic forcing plays a role is not clear (*78*).

Relative to the Indian Ocean, the Atlantic Ocean appears to have a greater influence on Pacific decadal variability in recent decades, and this can be conducted via extratropical and tropical pathways. One proposed extratropical pathway is that a warm North Atlantic SST anomaly weakens storm tracks over the North Atlantic and the North Pacific mid-latitudes, generating an anomalous North Pacific high pressure and a PNA pattern over the North Pacific *(85)*. Another proposed extratropical connection is that warming in the North Atlantic enhances local convection but increases subsidence in the North Pacific, contributing to the high pressure over the subtropical North Pacific, which decreases the wind speed of the subtropical North Pacific westerlies and induces a north-western subtropical Pacific warming through the WES effect and other processes *(86)*. However, recent research suggests that these extratropical pathways play a minor role compared to the tropical pathway *(87)*. Tropical Atlantic warming drives a convective response and an associated diabatic atmospheric heating anomaly, the magnitude of which is dependent on the magnitude of Atlantic SST anomalies relative to the tropical mean SSTs. This difference can be represented by a tropical Atlantic-minus-Pacific trans-basin SST gradient (red curve, **Fig. 3C**), also called Trans-Basin Variability (TBV) *(16, 88)*. The tropical Atlantic diabatic heating leads to a Gill-type (**Box 1**) response that results in an anomalous rising Walker circulation branch over the tropical North Atlantic and an anomalous sinking branch over the tropical central and eastern Pacific *(16, 17, 75, 87, 89, 90)* (**Fig. 3B**). The associated surface circulation anomalies lead to WES-induced surface cooling in the eastern/central Pacific and warming in the off-equatorial western Pacific. These processes intensify the Pacific Walker circulation through the Bjerknes feedback and lead to a La Niña–like state within the Pacific *(16, 17)*, mechanisms similar to those that trigger La Niña by the equatorial Atlantic warming on interannual timescales *(91)*.

Tropical Atlantic forcing of the Pacific can also be enhanced through the Indian Ocean, whereby the Atlantic Ocean-forced Indo-Pacific easterly wind anomalies of the Gill-type response generate the Indo-Pacific warming via the WES effect *(17)*. This Indo-western Pacific warming in turn intensifies the La Niña-like response by enhancing the Pacific trade winds through a mechanism similar to the IOB's role in the transition from El Niño to La Niña *(3, 38)* (**Fig. 3D**).

The Atlantic influence in recent decades can be reproduced in coupled simulations forced with SST anomalies only in the tropical Atlantic *(16, 17)*. This includes a La Niña-like state that is shown to lead to a higher frequency of La Niña than El Niño events *(87)*, which is consistent with observations since 2000. Similar coupled simulations forced with Indian Ocean SST anomalies find only a limited role for the recent observed Indian Ocean warming alone *(16, 17)*. Thus, since the late 1990s, the tropical Atlantic warming appears to have affected the entire tropics, while the induced Pacific response has contributed to the global temperature hiatus and its many regional impacts *(11)*. However, it is not clear whether, or to what extent, the rise of the Atlantic influence is related to the loss of connectivity between the Indian and Pacific Oceans. It remains an open question as to what caused the recent (1992–2011) decadal warming trend in the tropical Atlantic or what is the relative importance of internal variability and external forcing *(92)*.

Implications of pan-tropical interactions

Classical prediction frameworks rely only on internal Pacific precursors such as the equatorial Pacific warm water volume *(93, 94)*, which leads the ENSO SST signal by 6-9 months. The fact that ENSO properties and the Pacific decadal changes are affected by the Indian and Atlantic Oceans offers additional precursors (green and purple boxes, **Fig. 4, A to C**). However, these precursors are not well simulated by the majority of climate models (**Fig. 4, D to F**).

Knowledge of Indian Ocean conditions has been shown to improve ENSO forecasts *(4, 32)*. Incorporating information from an extreme positive IOD leads to improved prediction of the 1994/95 CP El Niño and of the intensity of the extreme El Niño in 1997/98; incorporating information of the IOD and the IOB combined improves the predicted ENSO evolution *(32)*, particularly the phase transition from an El Niño to La Niña *(4)*. In a similar vein, knowledge of Atlantic SST conditions improves ENSO prediction in dynamical and statistical models *(90, 95,* *96)*. Hindcast experiments with additional equatorial Atlantic SST information increases predictability of the major 1982/1983 and 1997/1998 El Niño events *(95)*. Further, NTA SST offers an independent precursor for ENSO. For example, since 1980, three out of the four cases of boreal spring NTA cooling (i.e. 1986, 1994, and 2009) were followed by a CP El Niño in winter, and all cases of boreal spring NTA warming (i.e., 1980, 1988, 1998, and 2010) were followed by a Pacific La Niña *(91)*. Since the NTA and the equatorial Atlantic contribute to predictive skill over the central and eastern Pacific, respectively *(91)*, these Atlantic precursors may offer potential for prediction of ENSO diversity.

Combining Indian and Atlantic Ocean precursors (**Fig. 4, A to C**) with those internal to the Pacific may considerably increase ENSO prediction skill *(53)* (**Fig. 4G**), particularly in recent decades (**Fig. 4H**). Enhanced ENSO prediction as a result of incorporating inter-basin precursors, in turn, could contribute to Atlantic and Indian Ocean climate prediction. Dynamical prediction experiments show that incorporating tropical Pacific information greatly enhances the predictive skill of the IOD and the IOB *(97)* and the tropical Atlantic climate *(98)*. Understanding pan-tropical interactions is therefore crucial for improving prediction of interannual tropical climate, its atmospheric teleconnections, and its global impacts.

The Atlantic contribution to Indo-Pacific climate predictability extends to multi-year timescales. Although internally generated decadal climate variability in the extratropical North Atlantic and North Pacific is predictable by up to half a decade in advance *(99, 100)*, such skill is still elusive for tropical climate. The influence of tropical Atlantic SST variability associated with the AMV can be utilized for Pacific decadal prediction *(87, 101)*. Such prediction skill is achieved via a global reorganization of the Walker circulation, which can be represented by a TBV index measuring the tropical SST gradient between the Pacific and the other two oceans *(101)*. The index displays predictability at multi-year lead times with contributions from the Atlantic and Indian Oceans. In particular, the Atlantic influence considerably increases decadal predictability in the central Pacific SST *(88)*.

Most state-of-the-art climate models fail to reproduce the observed pan-tropical interactions. In addition to an underestimated influence on ENSO from the NTA *(102)*, equatorial Atlantic variability *(22)*, and the IOD *(103)* (**Fig. 4, D to F**), the majority of models produce too weak of a relationship between decadal trends of the TBV and Pacific trade winds *(21)*. In fact, the relationship between trends of tropical Atlantic SST and equatorial Pacific trade winds is opposite to that observed in most models *(21)*. This unrealistic relationship is partially associated with a bias in the tropical Atlantic mean state *(20, 21)*, which features a weaker than observed, or even reversed, west-minus-east equatorial SST gradient. This bias leads to a weak convective response to Atlantic SST anomalies and a weaker Walker circulation response that is shifted to the east, the consequence of which is an unrealistic relationship between the Atlantic and Pacific *(20)*.

Systematic model errors in pan-tropical interactions may be in part responsible for the inability of models to simulate the recent global warming hiatus *(20, 103)*, in which greenhouse warming was offset by a cooling trend in the tropical Pacific *(11, 12)*. Further, faster warming in the Indian Ocean than the Pacific, as observed over the past decades, is conducive to easterlies in the western Pacific *(18, 84)*, through mechanisms similar to those operating on interannual timescales associated with an IOB warming *(3)*. Given that Indian Ocean warming is at least in part driven by Atlantic warming in recent decades *(17)*, systematic errors in the Atlantic-Pacific relationship might have suppressed important processes. The suppression of these processes may be responsible for the projected greater warming in the equatorial eastern Pacific under greenhouse warming. Therefore, correcting the biases in the Atlantic-Pacific relationship may lead to reduced eastern equatorial Pacific warming in climate projections.

Without properly accounting for Atlantic-Pacific and Atlantic-Indian Ocean interactions, the potential for an Atlantic warming-induced Pacific cooling is muted. Thus, this bias may have far reaching implications for projections of future climate, particularly in Pacific mean state change. For example, models exhibiting a stronger correlation between decadal trends of the TBV index and equatorial Pacific trade winds tend to project a weakened future warming in the tropical Pacific compared to those with a weaker decadal coupling (**Fig. 5, A and B**), supporting the notion that a realistic representation of pan-tropical interactions in climate models may substantially modify the projected Pacific mean state change *(22)*.

Summary and pathway forward

Pan-tropical interactions are more vigorous than previously thought and the three ocean basins are more tightly interconnected than previously realized. In addition to well-known Pacific Ocean influences on the Indian and the Atlantic Oceans, there are highly consequential feedbacks from these two basins on the Pacific on interannual to decadal timescales. For example, a positive NTA SST anomaly in boreal spring can trigger a central Pacific La Niña *(8, 10)*, whereas an equatorial Atlantic Niña in boreal summer can force an EP El Niño *(64)*, thereby contributing to ENSO diversity. Similarly, a positive IOD can favor the onset of El Niño and an El Niño-forced IOB can accelerate the demise of an El Niño and its transition to La Niña *(3, 4, 32)*. Modeling studies suggest that the net impact of the Indian and Atlantic Oceans on the ENSO cycle damps its amplitude and increases its frequency *(3, 38, 41, 42)*.

These tropical inter-basin linkages vary significantly on decadal timescales. In particular, tropical warming associated with the positive phase of the AMV over the past two decades represents a major forcing on the Pacific and Indian Oceans *(16, 17)*. This tropical Atlantic warming contributed to an extraordinary intensification of the Pacific trade winds accompanied by surface cooling in the eastern tropical Pacific, an increased ITF heat transport from the Pacific to the Indian Ocean, and an increased sequestration of heat in the Indian Ocean. A warmer Indian Ocean in turn also favored further intensification of the Pacific trade winds through changes in the Walker circulation *(17, 84)*. In this scenario, the tropical Atlantic emerges as pivotal in driving the recent hiatus in global surface warming.

Our knowledge of the pan-tropical inter-basin interactions is still in its infancy and many uncertainties exist. Given the relatively short observational record that dates back only to the second half of the 19th century, our ability to clearly define and understand inter-basin interactions across the full range of interannual to decadal and longer timescales is limited. For instance, available observations suggest that the sign of the AMV determines whether the equatorial Atlantic Niño (for negative AMV) or the NTA (for positive AMV) is the most active pathway of influence on the Pacific *(74)*. However, the relative importance of these two Atlantic SST modes in exciting inter-basin teleconnections is largely unknown. Whether these AMV influences are robust and what causes this multi-decadal modulation in inter-basin teleconnections are open questions.

Much of the new insight about the tropical Atlantic's role in tropical inter-basin interactions emerges from observations since 2000, when the AMV turned positive and reached its highest value in the instrumental record. It is unclear however what the relative importance of natural climate variability and anthropogenic forcing is in driving this Atlantic warming, whether the recent Atlantic influence on pan-tropical climate is reinforced by anthropogenic forcing, or how inter-basin interactions may affect the climate of the topics in the future. Climate modeling studies to address these issues are unfortunately compromised by pronounced systematic errors in the tropical Atlantic that severely suppress interactions with the Indian and Pacific Oceans *(20-22)*. These model biases in particular could have a substantial impact on the simulated ENSO characteristics and the Pacific mean state. As a result, there could be considerable uncertainty in future projections of Indo-Pacific climate variability and the background conditions in which it is embedded. Projections based on the current generation of climate models suggest that Indo-Pacific mean state changes will involve slower warming in the eastern than in the western Indian Ocean and a faster warming in the east equatorial Pacific than the surrounding regions *(104)*. Given the presumed strength of the Atlantic influence on the pan-tropics, projections of future climate change could be substantially different if model systematic errors in the Atlantic were corrected.

Nevertheless, recent advances in our understanding of the pan-tropical interactions provide valuable guidance for setting research priorities. Among these is the urgent need to reduce model systematic errors in the Atlantic as one key ingredient to enable further progress and there have been efforts to solve this *(105)*. It has been extraordinarily difficult to remedy such errors as we have learned from the Pacific cold tongue and double ITCZ biases, problems for which there has been no solution for decades. Thus, it is essential that we understand the fundamental processes that govern the Atlantic mean state, including interactions between tropical winds, SST, the upper ocean, atmospheric convection, and the role of equatorial ocean mixing. Given the shortness of the instrumental record, studies that take advantage of much longer paleo proxy records can be a valuable source of information on inter-basin interactions in the past. There is also potential for a substantial improvement in ENSO and multi-year predictions, by exploiting the dynamical linkages outside the Pacific basin *(88)*. Success on this front requires a deeper understanding of these linkages to ensure that they are represented as accurately as possible in forecast models.

Coordinated modeling studies, including pacemaker experiments, can be used to examine the mechanisms that underpin these tropical inter-basin interactions and their importance relative to extra-tropical influences. Given that the mean state errors in the tropical Atlantic are systematic, flux adjustments in climate models can also be a useful approach for exploring inter-basin interactions in the current climate and potentially in the future as well under differing climate change forcing scenarios. Ultimately, making progress in this enterprise will depend critically on sustained global climate observations, climate model improvements, and theoretical developments that help us to better understand the underlying dynamics of pan-tropical interactions and their climatic impacts.

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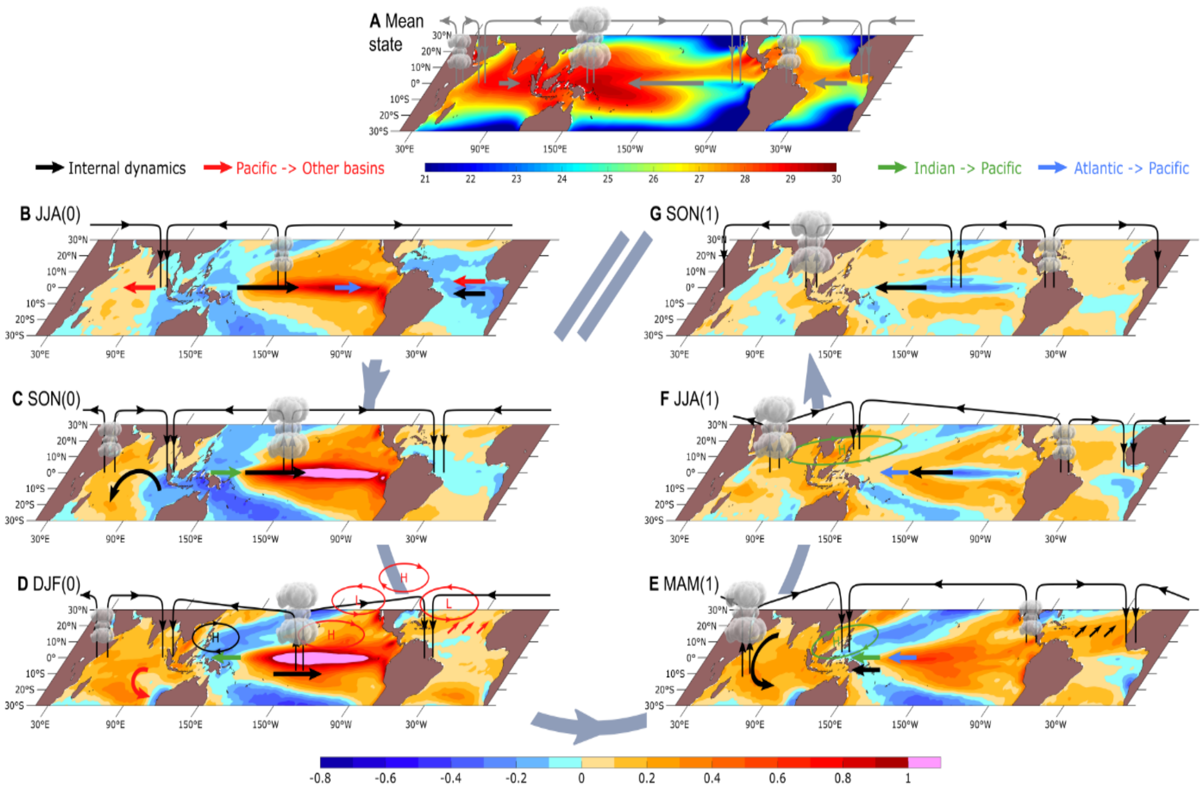

Fig 1: Evolution of tropical inter-basin interactions during a typical El Niño event. (**A**) Background mean state of SST (shading, [°C]) and Walker circulation (arrows). (**B-G**) Seasonally stratified SST anomaly lead/lag regression with normalized December-January-February (DJF) Niño3.4 (shading, [°C]) together with schematic surface wind and Walker Circulation changes (arrows). As El Niño grows, Walker Circulation changes lead to the development of (**B-C**) positive IOD, (**D-E**) IOB warming, (**B**) Atlantic Niña, and (**D-E**) NTA warming. (**D-E**) IOB and NTA warming induce equatorial wind anomalies in the Pacific, contributing to El Niño decay and transition to La Niña. (**F**) During post-El Niño summer, North Indian Ocean warming is coupled with the anomalous Northwest Pacific anticyclone, impacting Asian summer monsoon. Meanwhile, a developing La Niña in the Pacific favors Atlantic Niño conditions. The remaining seasons are abbreviated by March-April-May (MAM), June-July-August (JJA), and September-October-November (SON). Year 0 indicates an El Niño developing year, while year 1 indicates the subsequent decaying year.

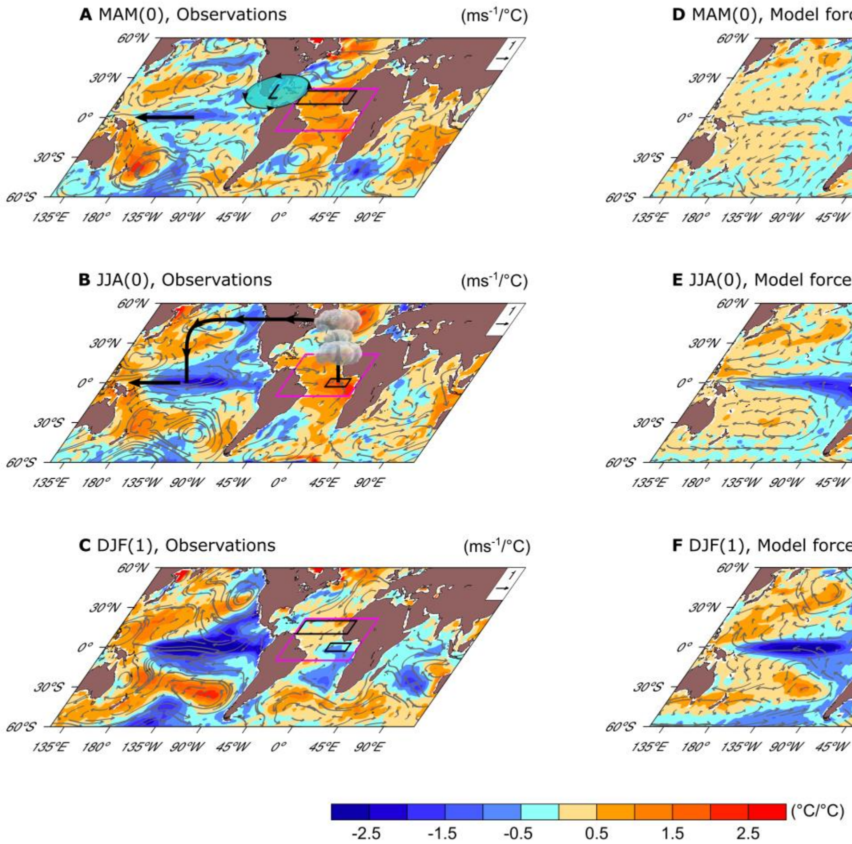

Fig. 2: Tropical Atlantic influence on the Pacific. (**A**) Observed 1980-2005 SST and 850hPa wind anomalies in MAM(0) regressed onto a basin-wide SST index over the tropical Atlantic (10°S-20°N, 60°W-10°E, purple box) in MAMJJA(0). This basin-wide index is selected to jointly capture the NTA (northern black box) and Atlantic Niño (southern black box) indices. The linear relation to the DJF(0) Nino3.4 index has been removed prior to the regression. NTA warming in MAM(0) generates a low-level cyclone over the eastern Pacific/Central America and easterly winds over the western equatorial Pacific through atmospheric Rossby and Kelvin wave responses. (**B**) In JJA(0), warming in the equatorial Atlantic induces anomalous Walker circulation, leading to anomalous easterlies in the central-western Pacific. (**C**) DJF(1), following the warming in the tropical Atlantic, cold anomalies develop in the central and eastern Pacific. (**D-F**) as in (**A-C**), but for a five member ensemble mean from pacemaker experiments performed over 1980-2005, in which full coupling is permitted everywhere except in the tropical Atlantic (30°S-30°N), where SSTs are nudged to observations (*70*).

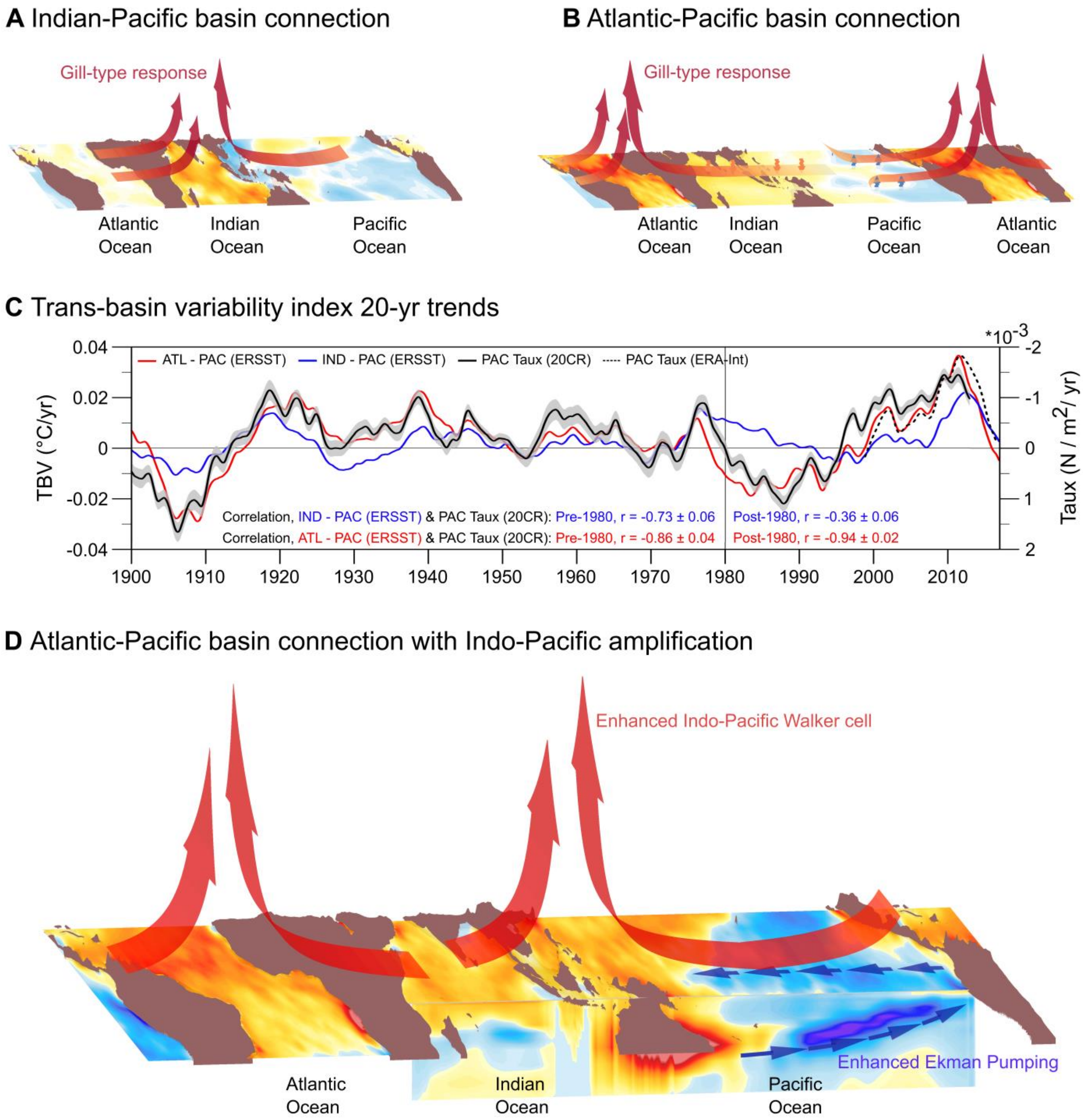

Fig 3: Decadal inter-basin connections with the Pacific. (**A**) Deep convection generated via Indian Ocean warming creates a Gill-type response that increases surface easterly winds and cold SSTs in the western Pacific. (**B**) Deep convection generated via Atlantic Ocean warming creates a Gill-type response, generating anomalous easterlies over the Indian Ocean and western Pacific. These anomalous winds lead to SST warming over the Indian Ocean and SST cooling over the western/central Pacific. The Gill-type response over the Atlantic also enhances the off-equatorial easterlies and cool SSTs in the eastern tropical Pacific. (**C**) Sliding window 20-year trends of inter-basin SST differences and equatorial western Pacific wind stress (recorded at end year of the

window). The wind stress and its one-standard deviation spread (shading) are from a 56-member reanalysis of the 20th century climate. Pre- and post-1980 correlations between the trans-basin SST and the ensemble-mean equatorial zonal wind trends are provided, together with one-standard deviation spread of correlations from the 56 realizations. Since 1980, the Atlantic-Pacific SST difference displays a stronger relationship with the Pacific winds than the Indian-Pacific SST difference. Indian, Pacific, and Atlantic basin SST are calculated between 20°S-20°N/21°E-120°E, 20°S-20°N/121°E-90°W, and 20°S-20°N/70°W-20°E, respectively. The Pacific wind is computed between 6°S-6°N/180°E-210°E. (**D**) The atmospheric circulation and surface temperature changes generated due to Atlantic warming in (**B**) are amplified by the Pacific Bjerknes feedback (**Box 1**) and IOD-Pacific interactions. The depth-longitude section in (**D**) illustrates the subsurface temperature and circulation anomalies in the Indo-Pacific.

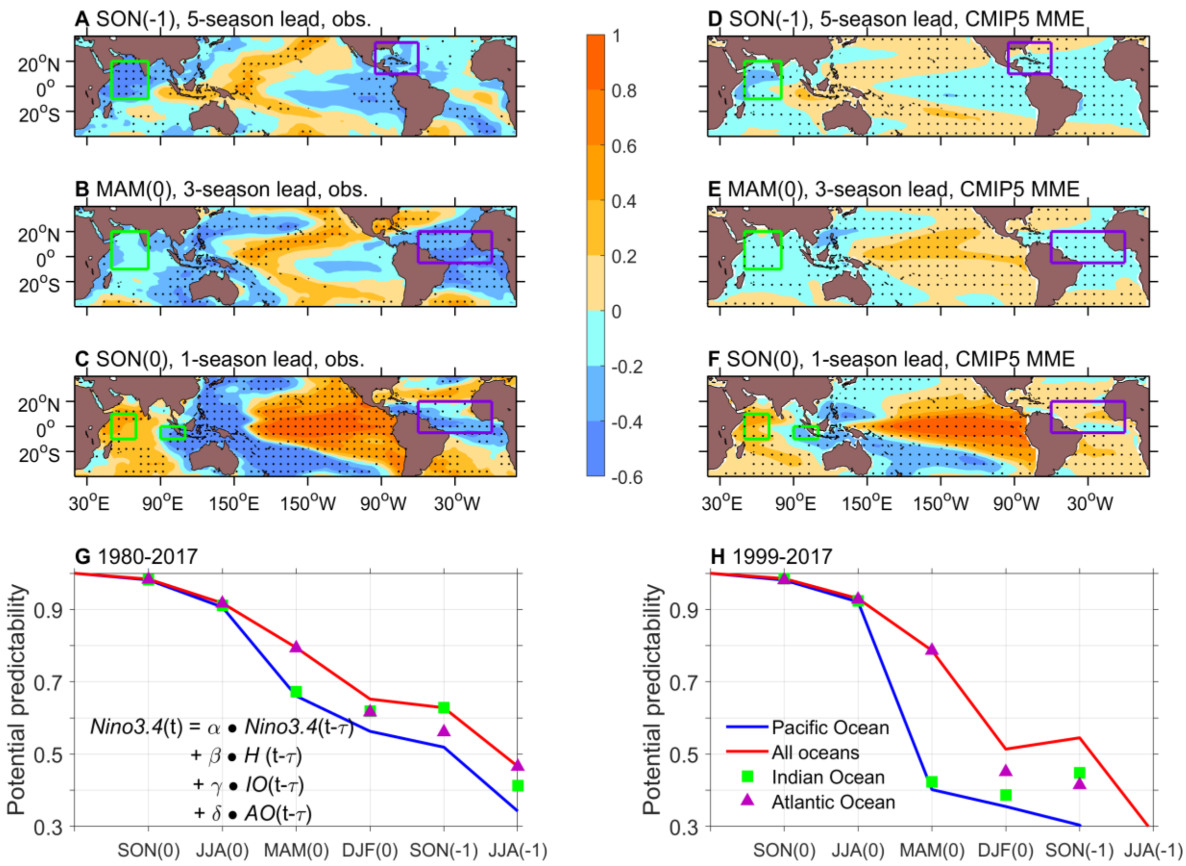

Fig 4: Potential predictability of ENSO from inter-basin predictors. Lag correlation between November-December-January (NDJ) Nino3.4 SST and (**A**) 5-seasons preceding SST (SON), (**B**) 3-seasons preceding SST (MAM), and (**C**) 1-season preceding SST (SON) during the period of 1980-2017. Stippling in (**A-C**) indicates significant correlations at the 90% confidence level based on Student's t-test. Green and purple boxes in (**A-C**) denote the areas used for predictors of multiple regression in (**G**) and (**H**), for the respective seasons. The location of the green and purple boxes are chosen from areas with the strongest NDJ Niño3.4 correlation for each season. (**D-F**) as in (**A-C**), but for the ensemble mean of 43 CMIP5 models. Stippling in (**D-F**) indicates regions where 66% of models agree with the sign of the ensemble mean. Correlation between observed NDJ Niño3.4 SST and reconstructed Niño3.4 SST from multiple regression with preceding predictors, as identified by strong regression coefficients, for the period of (**G**) 1980-2017 and (**H**) 1999-2017. Shown are results using internal Pacific predictors of western Pacific heat content (blue line), adding Indian Ocean (green squares), Atlantic (purple triangles), and both the Indian Ocean and the Atlantic Ocean predictors (red line).

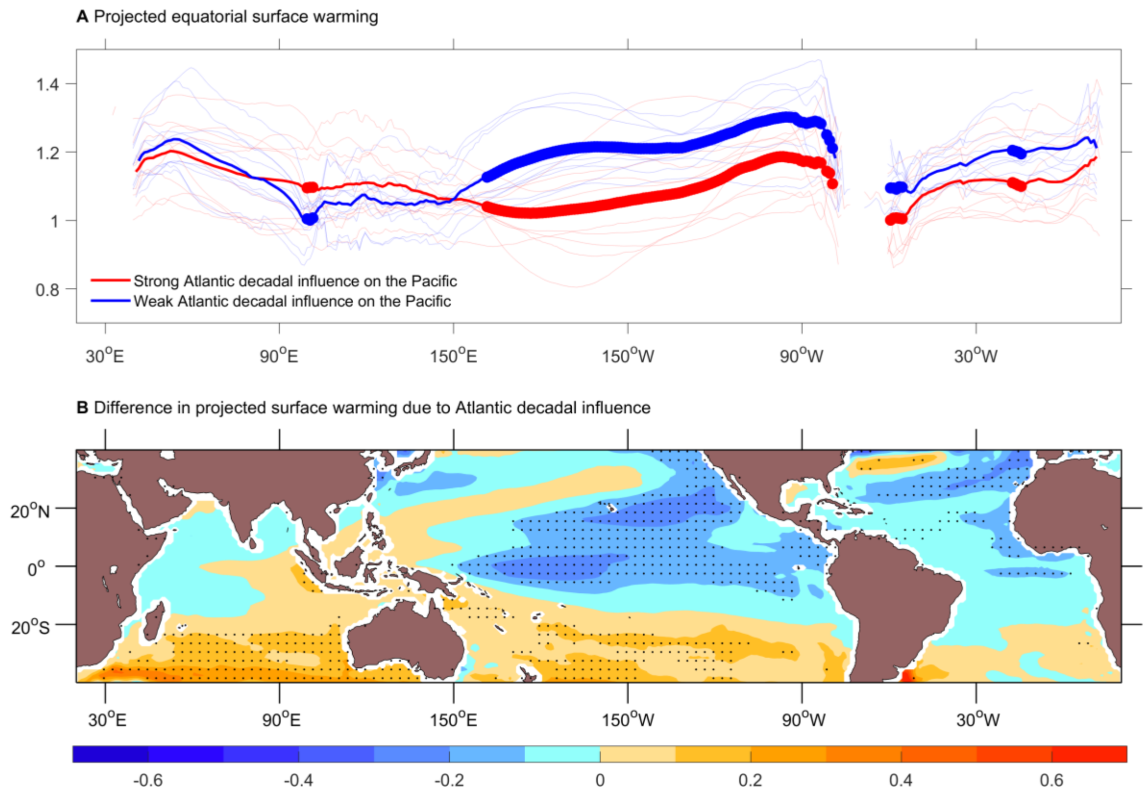

Fig. 5: Impacts of model errors in decadal Atlantic-Pacific relationship on future climate projections. (**A**) Future projections of equatorial (5°S-5°N) SST (per degree of global warming) in

two ensembles of 10 CMIP5 models (thin curves) with a strong (red) and weak (blue) coupling between decadal trends of an Atlantic-Pacific trans-basin variability index and equatorial Pacific trade winds as in Ref. (*18*). Models with a stronger coupling tend to generate a weaker warming. Changes are calculated as the difference in averages between the RCP8.5 2070-2099 and the historical 1980-2009 period, divided by the global mean SST change over the same periods. The broad thick curves denote where the difference between the two ensembles means (thick curves) are significant at the 95% confidence level, based on Student's t-test. (**B**) Differences in climatological SST changes between the two 10-model ensemble means. Stippling indicates areas where the ensemble mean difference is significant at the 95% confidence level, based on a Student's t-test.

Box 1: Key Concepts Defined

Atlantic Multi-decadal Variability (AMV) is a multi-decadal variation in sea surface temperature, sometimes also referred to as the Atlantic Multi-decadal Oscillation (AMO). The ultimate causes of this variability are the subject of ongoing research.

Atlantic Niño and Niña are generated along the equator in the Atlantic Ocean through ocean-atmosphere interaction processes similar to those of ENSO, though they are weaker and shorter lived than Pacific events.

Atmospheric bridge is a dynamical connection between tropical oceans that is associated with variations of the Walker circulation.

Atmospheric Kelvin wave is an eastward propagating disturbance in the atmosphere. Kelvin waves extend over the full height of the atmosphere, with a surface expression in the wind field that affects ocean-atmosphere interactions.

Atmospheric equatorial Rossby wave is a westward propagating disturbance in the atmosphere. Equatorial Rossby waves have a smaller zonal and larger meridional extent compared to Kelvin waves and also affect the surface wind field and ocean-atmosphere interactions.

Bjerknes feedback is a positive feedback in which a weakened sea surface temperature gradient along the equator leads to a weakening of the trade winds, which in turn further weakens the sea surface temperature gradient. Equivalently, a strengthened sea surface temperature gradient intensifies the trade winds, which then reinforce the surface temperature gradient.

El Niño-Southern Oscillation (ENSO) arises in the tropical Pacific through ocean-atmosphere interactions involving Bjerknes feedback. It is the dominant mode of interannual climate variability on the planet. El Niño events with their maximum sea surface temperature anomalies in the eastern and central Pacific are referred to as EP El Niño and CP El Niño, respectively.

Gill-type response is a response to an equatorial heating anomaly, generating an equatorial atmosphere Kelvin wave and associated surface easterly wind anomalies to its east, and atmosphere Rossby waves and an associated pair of low pressure cells to its west, with cyclonic surface westerly anomalies straddling the equator.

Interdecadal Pacific Oscillation (IPO) is a basin scale multi-decadal fluctuation in sea surface temperature that is characterized in its positive phase by unusually warm tropics and cool subtropics, and in its negative phase by opposite tendencies.

Indian Ocean Basin (IOB) mode is a uniform warming or cooling of the Indian Ocean that occurs on interannual to decadal time scales.

Indian Ocean Dipole (IOD) is a mode of interannnual variability in the tropical Indian Ocean that arises from ocean-atmosphere interactions somewhat similar to those of ENSO, though IOD events are weaker and shorter lived than ENSO events.

North Tropical Atlantic (NTA) is a sensitive region typically between 5°-20°N that both affects, and is affected by, inter-basin interactions in the tropics.

Walker circulation is a series of zonal overturning cells in the atmosphere associated with regions of rising and sinking motion.

Wind-evaporation-SST (WES) effect occurs when surface winds weaken over warm water, which reduces evaporation and leads to further surface warming; or when surface winds strengthen over cold water, enhancing evaporation and inducing further cooling. The sign of the WES effect depends on whether the wind changes strengthen or weaken the mean winds.

Enhanced Abstract

BACKGROUND

Ocean-atmosphere interactions in the tropics have a profound influence on the climate system. El Niño-Southern Oscillation (ENSO), which is spawned in the tropical Pacific, is the most prominent and well-known year-to-year variation on Earth. Its reach is global and its impacts on society and the environment are legion. Because ENSO is so strong, it can excite other modes of climate variability in the Atlantic and Indian Oceans by altering the general circulation of the atmosphere. However, ocean-atmosphere interactions internal to the Atlantic and Indian Oceans are capable of generating unique modes of climate variability as well. Whether the Atlantic and Indian Oceans can significantly feed back onto Pacific climate has been an ongoing matter of debate. We are now

beginning to realize that the tropics, as a whole, are a tightly interconnected system, with strong feedbacks from the Indian Ocean and the Atlantic Ocean onto the Pacific. These two-way interactions affect the character of ENSO and Pacific decadal variability and shed new light on the recent hiatus in global warming. Here we review advances in our understanding of pan-tropical inter-basin climate interactions and their implications for both climate prediction and future climate projections.

ADVANCES

ENSO fluctuates between warm events (El Niño) and cold events (La Niña). These events force changes in the Atlantic and Indian Oceans than can feedback onto the Pacific. Indian Ocean variations, for example, can accelerate the demise of El Niño and facilitate its transition to La Niña. ENSO events also exhibit significant diversity in their amplitude, spatial structure, and evolution, which matters for how they impact on global climate. Sea surface temperature variations in the equatorial and north tropical Atlantic can significantly contribute to the diversity of these events. In addition, tropical inter-basin linkages vary on decadal time scales. Warming during a positive phase of Atlantic Multi-decadal Variability (AMV) over the past two decades has strengthened the Atlantic forcing of the Indo-Pacific, leading to an unprecedented intensification of the Pacific trade winds, cooling of the tropical Pacific, and warming of the Indian Ocean. The Indo-Pacific temperature contrast further strengthened the Pacific trade winds, helping to prolong the cooling in the Pacific. These interactions forced from the tropical Atlantic were largely responsible for the recent hiatus in global surface warming. Changes in Pacific mean state conditions during this hiatus also significantly affected ENSO diversity.

OUTLOOK

There is tremendous potential for improving seasonal to decadal climate predictions and for improving projections of future climate change in the tropics though advances in our understanding of the dynamics that govern inter-basin linkages. The role of the tropical Atlantic in particular requires special attention since all climate models exhibit systemic errors in the mean state of the tropical Atlantic that compromise their reliability for use in studies of climate variability and change. Projections based on the current generation of climate models suggest that

Pacific mean state changes in the future will involve faster warming in the east equatorial basin than the surrounding regions, leading to an increase in the frequency of extreme El Niños. Given the presumed strength of the Atlantic influence on the pan-tropics, projections of future climate change could be substantially different if model systematic errors in the Atlantic were corrected. Progress on these issues will depend critically on sustaining global climate observations, climate model improvements especially with regard to model biases, and theoretical developments that help us to better understand the underlying dynamics of pan-tropical interactions and their climatic impacts.

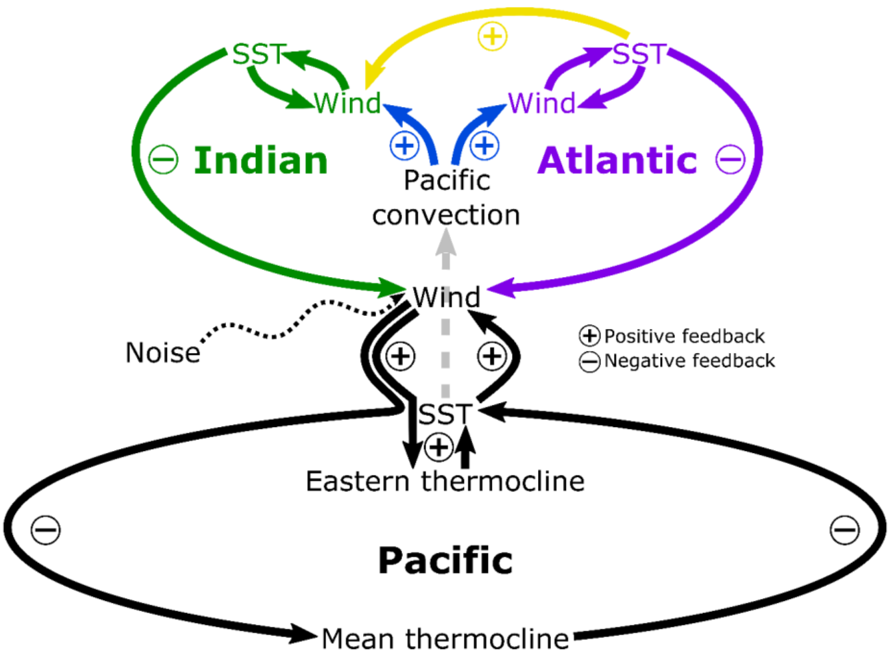

Fig. 0: Pan-tropical feedbacks affecting ENSO. Black loop represents internal Pacific fast positive feedbacks (short arrows) and delayed negative feedbacks (long arrows). Inter-basin feedbacks include Pacific feedbacks onto the Atlantic and Indian Oceans (blue arrows), delayed negative feedbacks of the Atlantic and Indian Oceans onto the Pacific (green/purple arrows) and positive feedbacks of the Atlantic onto the Indian Ocean (yellow arrow). The effects of atmospheric noise forcing in the Pacific is indicated by the dotted line.